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Dear Stan:

I thought that you might
enjoy having the enclosed paper.
When I was in your office at the
CIA, I noticed a picture of
Jupiter in your outer office.
We took that picture about five
years ago and the enclosed
paper explains how it was
done -

Best Regards,

Haus.

(EXECUTIVE SECRETARY OF THE AIR FORCE)

Air Force

The journey to Jupiter

Charles F. Hall, Hans Mark, and John H. Wolfe

Jupiter has always had a special fascination for mankind. It is very brilliant and it is steady in the sky, being one of the slower moving planets. This circumstance is probably why it was named after the king of the gods in the Roman Pantheon. Jupiter has also had a truly remarkable place in the history of modern science for almost four centuries. The two Pioneer spacecraft missions described here have now greatly advanced our knowledge of Jupiter, its satellites and interplanetary space.

In the year 1610 Galileo Galilei first turned a primitive telescope on Jupiter. In doing so he discovered the four brilliant 'Galilean' satellites of the planet. The discovery of the satellites of Jupiter was an extremely important scientific event but its cultural impact was even greater. For the first time man saw a 'quasi-solar system' from the outside. It is likely that Galileo's observation was the decisive factor in providing the framework for the eventual acceptance of the Copernican model of the solar system in preference to the earlier Ptolemaic or geocentric version.

A second important discovery was made by the Danish astronomer Ole Rømer working in Paris in 1676. Rømer used the occultation of the satellite Io by Jupiter to make the first determination of the speed of light. He noticed that the period of occultation varied slightly depending on whether the Earth was moving away from or toward the planet. He correctly interpreted this phenomenon as the result of the finite propagation velocity of light and obtained a remarkably accurate measurement of that velocity by making the appropriate calculations.

Much information has been gained about Jupiter since then. Improved telescopes led to the discovery of the spectacular bands on the surface of the planet and the mysterious red spot in the 17th century. More recently, radio wave emissions have been observed arising from the complex electromagnetic interactions occurring in the planet's magnetosphere and upper atmosphere. Finally, spectroscopic measurements using modern instruments have yielded important information on the composition and the behaviour of Jupiter's upper atmosphere.

The observations and measurements outlined here set the stage for the next great step in the exploration of Jupiter—an actual visit to the planet by an instrumented space probe.

The Pioneer 10 and 11 spacecraft

The Pioneer exploration of Jupiter with an unmanned spacecraft began in 1968 when, on the recommendation of the U.S. National Academy of Sciences Space Science

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Board, it was decided to undertake a project to send two spacecraft to Jupiter. The stated scientific purposes of the mission were: (1) The exploration of interplanetary phenomena. (2) The study of the asteroid belt. (3) The 'in situ' measurement of the environment of Jupiter.

The two Pioneer spacecraft are almost identical, each one carrying twelve instruments as listed in Table 1. In addition to the twelve instruments the S-band telecommunication system signal was used to perform measurements on Jupiter's ionosphere when the spacecraft were occulted by the planet. The S-band tracking was also employed to get a more accurate measurement of the gravitational field of the planet and the masses of the Galilean satellites. There was a minor change in the payload of Pioneer 11 as compared to Pioneer 10 in that a fluxgate magnetometer was added for the second flight.

The Pioneer 10 and 11 spacecraft are relatively small and simple spin-stabilized vehicles weighing approximately 258 kg. The total science payload weight is about 30.4 kg and the payload uses 25 W of electrical power provided by four radioisotope thermo-electric generators. These operate on the heat produced by the radioactive decay of a quantity of plutonium 238. The S-band communications system requires a 2.74 m diameter high-gain antenna reflector. The bit rate capacity of the system at maximum is 2048 bits s⁻¹. The antenna is rigidly mounted on the spacecraft in such a way that the spacecraft can always be pointed toward the Earth. The spin axis of the spacecraft is in the plane of the ecliptic and the spin axis is precessed occasionally with small gas jets to keep the antenna dish properly oriented. The spin rate normally is approximately 4.8 rev/min.

Figure 1 is a line drawing of the spacecraft depicting the locations of the various instruments carried by the spacecraft. The power supplies are located on the two booms, as shown, to prevent radiation produced by the decay of the ²³⁸Pu from seriously affecting the radiation detection instruments mounted on the spacecraft. The magnetometer experiment also must be mounted on a long boom so that the very sensitive helium vector magnetometer is removed from the spacecraft to prevent stray magnetic fields produced by the electronic equipment in the spacecraft from disturbing the readings.

Pioneer 10 was launched on 3 March 1972 and encountered Jupiter on 4 December 1973. The spacecraft was launched using an Atlas Centaur launch vehicle with a third stage solid-fuel motor from the NASA Launch Complex at Cape Canaveral. Pioneer 10's Jupiter encounter trajectory was such that the spacecraft gained speed as a result of the encounter. In fact, Pioneer 10 gained enough speed to become the first man-made object to leave the solar system. Pioneer 11 was launched on 6 April 1973, also using an Atlas Centaur launch vehicle with a third stage. It reached Jupiter on 3 December 1974. The trajectory in this case came closer to the Jupiter cloud tops than did Pioneer 10, at a distance of 43 000 km compared with 131 000 km for Pioneer 10. After the encounter the Pioneer 11 spacecraft was directed to make a close

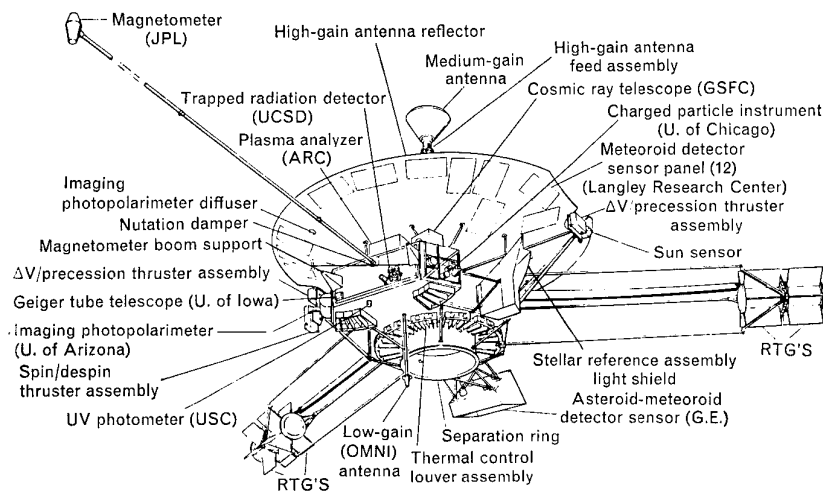


Figure 1 The Pioneer 11 Spacecraft. (Figures 1-4 and 7 appeared in *Science*, N.Y., 188, 445-79, 1975 and are reproduced by permission of the publishers and respective authors.) (Copyright 1975 by the American Association for the Advancement of Science)

flyby of the planet Saturn late in 1979. Figure 2 shows the trajectory geometry of the two spacecraft looking down from above the plane of the ecliptic. Figure 3 shows the trajectories roughly edge-on to the plane of the ecliptic. Pioneer 11 is the first man-made object substantially to leave the ecliptic plane. Its orbit now has an inclination of about 15.9 degrees with the plane of the ecliptic. At its maximum Pioneer 11 will be about 1.1 A.U. out of the ecliptic. The two trajectories allowed a very thorough exploration of Jupiter's environment.

Experimental results

Micrometeorite experiment. The object of this experiment was to measure the micrometeorite particle flux in the interplanetary medium. The detector consisted of 234 pressurized cells mounted on the back of the parabolic reflector dish. The detectors are covered with thin sheets of stainless steel that would be pierced by small high-velocity particles striking the spacecraft. An electric field is maintained across each cell as long as the cell is at atmospheric pressure. When the window is pierced by a micrometeorite, the gas leaks out and at a certain pressure a discharge is observed. The discharge gives rise to a pulse which is counted by an appropriate electronic circuit. On Pioneer 10 the thickness of the stainless steel windows was 25 μm making the detector sensitive to particles as small as 10^{-9} g. On the Pioneer 11

spacecraft the windows were twice as thick, the sensitivity limit then being 10^{-8} g.

The results of the micrometeorite experiment are shown in figure 4 in which the number of 'hits' are plotted as a function of the time of flight for both spacecraft. The most striking feature of the curve is that there is no increase in the 'hit' rate in the region of the asteroid belt between the orbits of Mars and Jupiter. Thus, there are no small particles accompanying the larger objects that are known to populate the asteroid belt. The other interesting feature of the curve is that there is an increase in the counting rate during the encounter with Jupiter. This increase is probably caused by small gravitationally focused particles close to the planet itself.

Plasma and magnetic field experiments.

The object of these measurements

was twofold. One was to look at the behaviour of the interplanetary plasma and magnetic fields between the Earth and Jupiter. The other was to observe the very complex interactions between the solar plasma, that is the solar wind, and the magnetosphere of Jupiter. Both aims were achieved.

In the case of the interplanetary plasma, the Pioneer 10 and 11 spacecraft joined the earlier Pioneers (6 to 9) in monitoring the solar plasma or the solar wind on a continuing basis. Pioneers 6 to 9 were a series of solar orbiting spacecraft launched in the late 1960s with the primary purpose of monitoring the solar plasma. These spacecraft are all in orbits having radii of approximately 1 astronomical unit (A.U.). Pioneers 10 and 11 are very much further from the Sun. In several instances, disturbances first observed by one of the earlier Pioneers at 1 A.U. were later measured by Pioneers 10 or 11, thus enabling us to obtain a more accurate dynamic map of the plasma field created by the Sun.

In the vicinity of Jupiter, the plasma probe was most important in mapping the interaction of the solar wind with Jupiter's magnetosphere. In each flight a shock wave created by the impingement of the solar wind on Jupiter's magnetosphere was observed at a distance of about 100 Jupiter radii (7×10^6 km) from the planet. A turbulent plasma layer exists behind the shock which was also observed in detail and this region, the 'magneto-

sheath', is then followed by the magnetic field of the planet itself. The magnetic axis of Jupiter is tilted with respect to its axis of rotation at an angle of approximately 10.8° . Since Jupiter's rotation time around its axis is very short—ten hours—and since the dipole field is essentially fixed to the magnetic axis, this leads to a rapidly fluctuating set of measurements when observed from a platform in a hyperbolic orbit around the planet. These rapid fluctuations will become particularly apparent in the discussion of the charged particle measurements in Jupiter's vicinity.

The magnetosphere in its outer regions is relatively 'soft' as evidenced by the observation that the position of the shock structure changes in time depending on the pressure exerted

Table I
Instrumentation on Pioneer 11

Instrument	Institution	Principal Investigator
Helium vector magnetometer	Jet Propulsion Laboratory (JPL)	E. J. Smith
Flux-gate magnetometer	Goddard Space Flight Center (GSFC)	M. Acuna
Plasma analyser	Ames Research Center (ARC)	J. H. Wolfe
Charged-particle detector	University of Chicago	J. A. Simpson
Geiger-tube telescope	University of Iowa	J. A. Van Allen
Cosmic-ray telescope	Goddard Space Flight Center (GSFC)	F. B. McDonald
Trapped radiation detector	University of California, San Diego (UCSD)	R. W. Fillius
Ultraviolet photometer	University of Southern California (USC)	D. L. Judge
Imaging photopolarimeter	University of Arizona	T. Gehrels
Infrared radiometer	California Institute of Technology	G. Münch
Asteroid-meteoroid detector	General Electric Company (G.E.)	R. K. Soberman
Meteoroid detector	Langley Research Center	W. H. Press

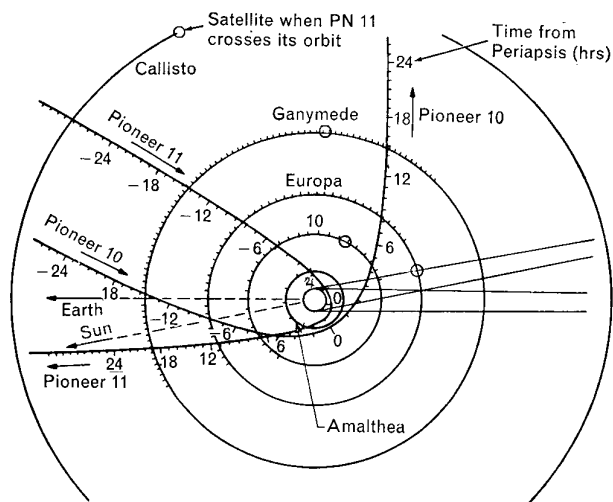


Figure 2 The Pioneer 10 and 11 trajectories as projected on the plane of the ecliptic.

on it by the solar wind. The picture that emerges from the plasma and the magnetic measurements is shown in figures 5 and 6. The bow shock, the magnetosheath, the magnetosphere, and the dipole field are all shown. Measurements made by Pioneer 10 and 11 indicate that the magnetic field at the surface of Jupiter is 10-14 gauss. This is about 20 times larger than the value of the Earth's magnetic field at its surface.

Charged-particle experiments. The Pioneer 10 and 11 spacecraft carried a full complement of charged-particle detectors. These devices were sensitive to electrons, protons, and heavier charged particles over a wide range of incident particle energies. As was the case for the plasma and the magnetic field experiments, there were two purposes in performing charged-particle measurements. The first was to measure the charged-particle species and energy distribution in interplanetary space, and the second was to perform similar measurements in the vicinity of Jupiter.

The charged-particle detectors differ from the plasma probe in that they are sensitive to particles having energies much higher than the 'thermal' energies encountered in the case of plasma measurements. The cosmic-ray background measurements revealed that the high-energy cosmic ray flux stays roughly constant as the spacecraft moves from the vicinity of the orbit of Earth

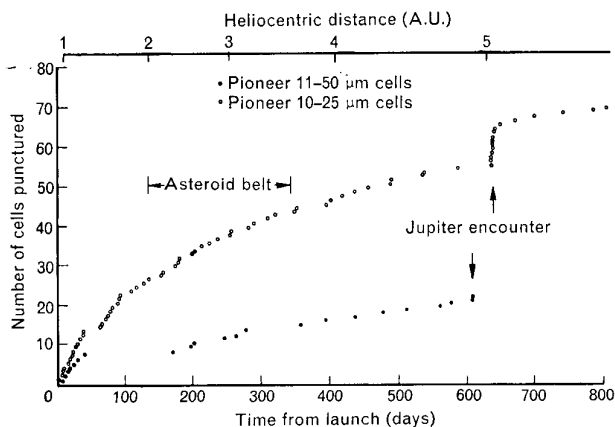


Figure 4 The number of 'hits' on the micro-meteoroid detectors on Pioneers 10 and 11 is shown in this figure as a function of time from launch.

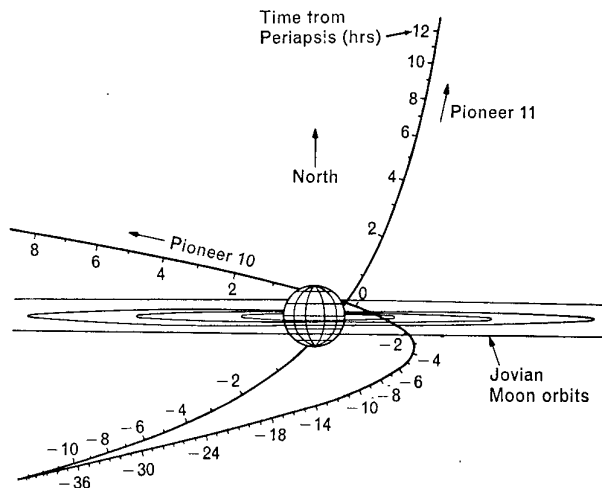


Figure 3 The Pioneer 10 and 11 trajectories as seen roughly from a point in the plane of the ecliptic.

to the orbit of Jupiter, 5 A.U. away. This result is to be expected in view of the galactic origin of the cosmic rays.

Near Jupiter very complex patterns of charged particles are observed. These arise because the dipole-shaped magnetic field of Jupiter acts in such a manner that energetic charged particles can execute long-lived, stable orbits in the field. Such particles are usually said to be trapped in the magnetic field. Both Pioneers 10 and 11 flew by the planet in such a way that really detailed measurements of the charged particles trapped in Jupiter's magnetic field were possible for the first time. Figure 7 shows the results of one of these charged-particle experiments. Its important features are:

- (1) Large fluctuations in the observed counting rate are

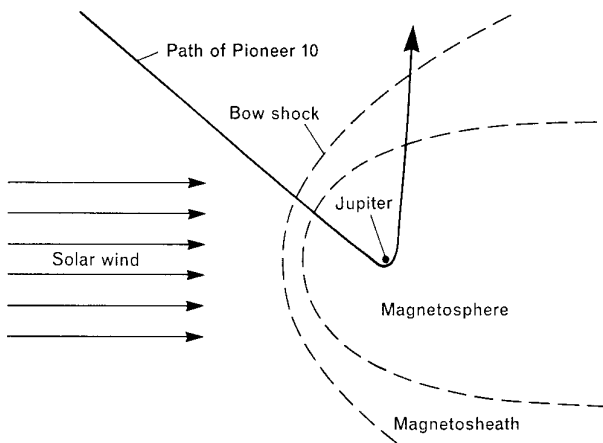


Figure 5 The structure of the bow shock and the magnetosphere are shown.

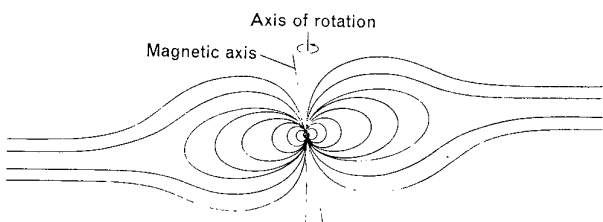


Figure 6 A schematic drawing of Jupiter's magnetosphere is shown.

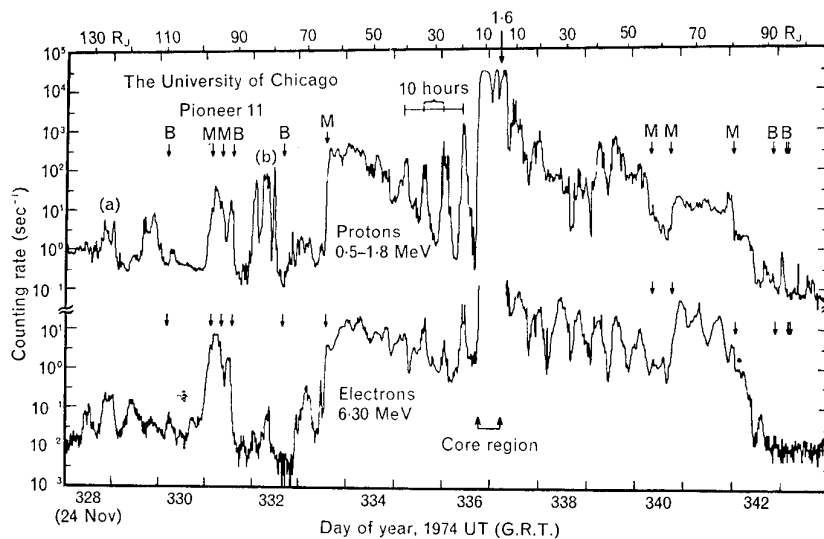


Figure 7 This figure shows the counting rates of the detectors sensitive to 0.5 to 1.8 MeV protons and 6 to 30 MeV electrons. Crossings of the bow shock are labelled (B) and magnetopause crossings are labelled (M).

seen, these being due to the rapid rotation of the planet and its associated dipole field.

(2) Higher counting rates are observed near the planet. This result is expected and is similar to that observed in the case of charged particles trapped in the Earth's magnetic field.

(3) Reductions in the counting rates are observed when the spacecraft passes over the orbits of the large satellites of the planet. This is caused by the fact that the charged particles trapped in the magnetic field strike the satellites and are thus lost from those regions of the magnetosphere traversed by the satellites.

(4) There is an asymmetry between the measurements made on the incoming and the outgoing portions of the orbits for both spacecraft. This observation results from the asymmetry of the magnetic environment of the planet illustrated in figure 5.

The charged particle measurements in the vicinity of the planet yielded a great deal of new information. However, a complete understanding of the magnetic and the charged particle environment must await the placing of an orbiting spacecraft around Jupiter that will enable many repeated measurements to be made of the particle fluxes and the magnetic fields in the vicinity of the planet. *Spectroscopy and photometry.* Several spectrometers were carried aboard the Pioneer 10 and 11 spacecraft to view the planet and its satellites. An ultraviolet photometer was set to detect lines characteristic of hydrogen and helium which are the important constituents of Jupiter's atmosphere. An infrared radiometer was used to make a complete thermal map of the planet. Finally, an imaging photo-polarimeter was mounted on both spacecraft. This instrument produced the spectacular pictures taken of Jupiter during the flybys of Pioneers 10 and 11. These pictures are by far the most detailed images ever obtained of the planet.

The most important result of the ultraviolet photometry is an estimate of the helium to hydrogen ratio in the upper atmosphere of Jupiter. The result is that He/H_2 is approximately 0.18, which is reasonable when compared with the solar helium to hydrogen ratio. The solar nebula, from which the Sun and planets were formed some 5×10^9 years ago, was composed mostly of hydrogen and helium. The terrestrial planets (Mercury, Venus, Earth, and Mars), however, did not

possess a sufficiently strong gravitational field to retain the hydrogen and helium and these light elements were quickly lost early in the formation of these planets. Jupiter, on the other hand, is so massive (approximately 318 times the mass of the Earth) that its elemental composition must be, today, essentially the same as the original solar nebula. The study of the helium/hydrogen ratio is, therefore, important for our understanding of the formation of our solar system. The helium/hydrogen ratio is also important as an engineering parameter in designing the heat shield for an entry probe that will eventually be flown on a future mission to Jupiter.

It had already been determined from ground-based measurements that Jupiter apparently radiates more energy—by about a factor of two—than it receives from the Sun. The word 'apparently' is used deliberately here to highlight the fact that only the 'bright' side of the planet is visible from the Earth. It is possible, but unlikely, primarily because of the rapid rotation rate of the planet, that the energy radiated from the planet's dark side is substantially different from that observed from the vantage point of the Earth. Since the spacecraft, during the flyby, viewed the dark side of the planet as well as the light, this matter could be settled once and for all. It was found during the flyby that the temperature of the planet is roughly uniform, irrespective of whether the dark or the light side is observed. The surface temperature is approximately 125 ± 2 K which is somewhat lower than the temperature estimated from observations made from the surface of the Earth (134 K). This measurement shows that the energy radiated by Jupiter is about 1.9 ± 0.2 times the energy the planet receives from the Sun. Since Jupiter is not large enough to burn in the thermonuclear sense (that is, the planet is not a star) the excess energy must either come from radioactive decay of heavy material in the core or, more probably, from residual heat left over from the initial gravitational collapse associated with Jupiter's original formation.

The pictures produced from the data provided by the imaging photo-polarimeter also yielded some extremely important scientific results. The most significant are:

- (1) The white bands on the planet's surface are at somewhat higher levels in the planet's atmosphere than the neighbouring dark bands. This was established by observing the terminator that marks the boundary between the sunlit and dark regions of the planet.
- (2) The 'red spot' on the planet's surface seems to be above the surrounding white belt in which it is located. This is consistent with the red spot being a cloud deck caused by a more or less permanent vortex in the planet's atmosphere. The red colour probably results from the material lifted from the lower layers of Jupiter's atmosphere above the uppermost cloud deck by the vortex.
- (3) There are a great many smaller vortex-like disturbances of a non-permanent nature on the planet's surface.
- (4) Jupiter's polar region has a mottled appearance rather than the characteristic stripes that are the major features of the equatorial region of the planet.

Figures 8 and 9 are pictures of the planet taken with the imaging photo-polarimeter that illustrate some of the points made in this section. It should be pointed out that

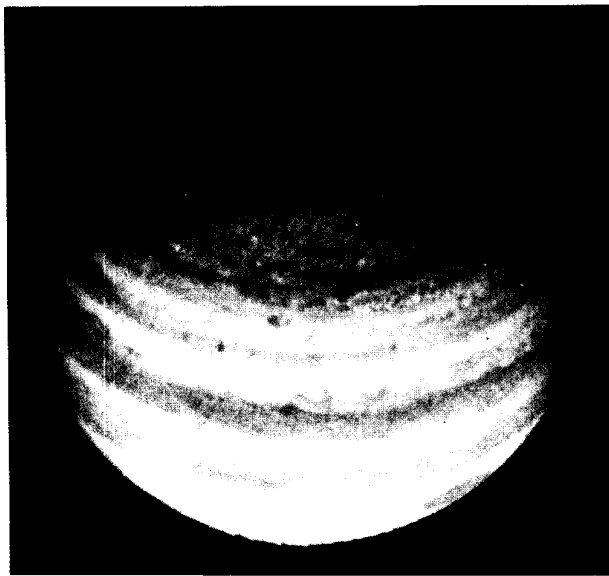


Figure 8 (above) This remarkable picture of Jupiter was taken by Pioneer 11 looking down on Jupiter from 50° north latitude. The north pole of Jupiter itself is roughly on the terminator line at the top of the picture. The Great Red Spot is shown, greatly foreshortened because of the location of the spacecraft, at the lower right. The polar regions of Jupiter cannot be observed from the Earth. (Figures 8, 9 and 10 are NASA/University of Arizona photographs).

Figure 9 (right) This close-up of Jupiter's Great Red Spot was taken from a distance of 545 000 km. Details visible within the spot seem to show a counter-clockwise spiral. The white oval below the right end of the Red Spot is one of three such spots about 120° apart around Jupiter.



the camera used was a spin-scan instrument and that the pictures themselves are computer constructs of the bit streams obtained from the spin-scan camera. The colours are obtained by superposing two images taken through a red and a blue filter in such a way as roughly to reproduce the colours of Jupiter when it is observed through a good optical telescope.

Figure 10 shows the satellite Ganymede taken with the same camera system. It is the first picture ever to show distinct surface features on one of the satellites of an outer planet in our solar system.

The atmosphere of Jupiter. Both Pioneer 10 and 11 performed radio wave absorption experiments when the spacecraft was occulted by the planet. An interpretation of the S-band occultation measurements yields an atmospheric temperature of about 400 K at the 5×10^4 Pa pressure level in the atmosphere. This result is in serious disagreement with that obtained using the infrared radiometer. At the present time there is no generally accepted explanation for the observed discrepancy.

Table II
Jupiter gravity harmonics from an analysis of Doppler data from Pioneer 10 (2) and Pioneer 11. Values are based on an assumed equatorial radius of 71 398 km.

Coefficient ($\times 10^6$)	Pioneer 10	Pioneer 11
J_2	$14\,720 \pm 40$	$14\,750 \pm 50$
J_3	< 150	10 ± 40
J_4	-650 ± 150	-580 ± 40
J_6	Assumed zero	50 ± 60

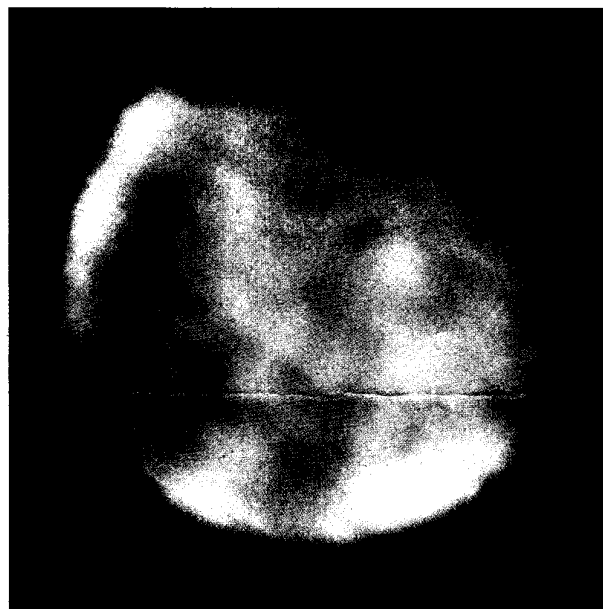


Figure 10 A picture of Ganymede taken from a distance of 751 000 km by Pioneer 10. Ganymede is somewhat larger than the planet Mercury. The surface resolution of the picture is about 400 km and it is by far the best picture taken yet of this body.

Table III
Mass and density of Galilean satellites

Satellite	Mass (Earth Moon=1)	Density g cm^{-3}
Io	1.22	3.5
Europa	0.67	3.14
Ganymede	2.02	1.94
Callisto	1.44	1.62

The gravitational field of Jupiter and the masses of the Galilean satellites. The orbits of both Pioneers 10 and 11 near Jupiter were tracked accurately by observing the Doppler shifts in the S-band communications carrier wave. The zonal harmonics of the gravitational field of Jupiter as determined from these measurements on Pioneer 10 and Pioneer 11 are shown in Table II. It can be seen that Jupiter's gravitational field has a substantial quadrupole component which is clearly caused by the oblate shape of the planet. The masses of the Galilean satellites were obtained from the same measurements. These are shown in Table III along with the densities estimated from the observed disc sizes of the satellites. It is remarkable that two of the satellites have densities near those of the terrestrial planets whereas the other two have densities that are comparable to the density of Jupiter and the other outer planets. This suggests that there may be close similarities between the formation of the Jovian system and the formation of the solar system.

Future prospects

Pioneer 10 is now on its way out of the solar system. It is estimated that the spacecraft may stay in contact until it has reached a distance of about 20 A.U. from the Sun. It is possible that the spacecraft will cross the boundary line between the solar plasma and the true interstellar space before it reaches the limit of its communication system. This would clearly be a most important event since it would yield for the first time a direct measurement of the particle density in the local part of our galactic space.

As already stated, Pioneer 11 has been targeted to reach Saturn at the end of 1979. The hope is that a similar set of experiments to the ones described here will be performed in the vicinity of this planet as well.

Beyond the Pioneers, several other flights to the outer planets are in the planning stage. In 1978 a Mariner probe with a more sophisticated complement of instruments than Pioneer will repeat the flight of Pioneer 11. It will first fly by Jupiter and then swing on an orbit to

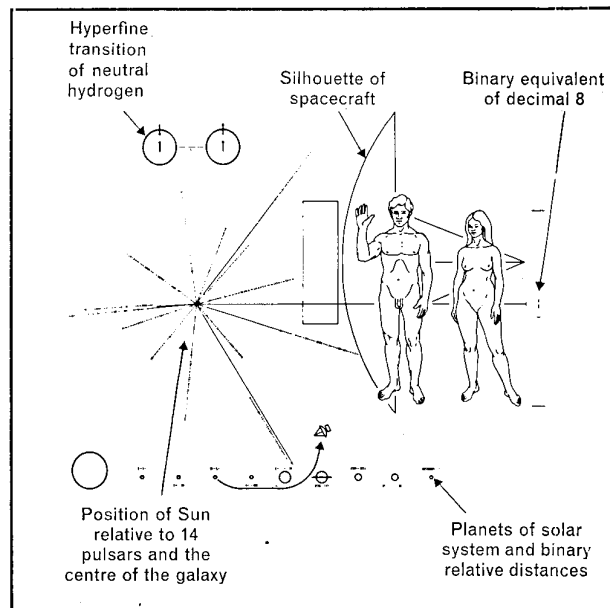


Figure 11 The Pioneer 10 plaque.

Saturn and fly by that planet once again. It is expected that among other things, much better photographs of both of these planets will be obtained from the Mariner flybys. In the early 1980s an orbiter will be placed around the planet Jupiter and then, perhaps, an atmospheric probe will be sent into the upper atmosphere of Jupiter. These new exploratory efforts are essential if we are to reach a complete understanding of the origin of our solar system.

No discussion of the Pioneer flybys of Jupiter would be complete without mentioning the plaque that was placed on the Pioneer 10 spacecraft. It has already been mentioned that the Pioneer 10 spacecraft is the first man-made object to leave the solar system. At the suggestion of Professor Carl Sagan of Cornell University, a plaque (figure 11) was attached to the spacecraft which is intended to inform any 'intelligent being' of the origin of the spacecraft. Perhaps the most important future prospect of all is that Pioneer 10 will be found by someone who can successfully decipher the plaque and then notify us that he has discovered our cosmic messenger.

Author's Note: All the technical data in this paper were published by the Pioneer 10 Principal Investigators in *Science*, N.Y., 183, No. 4122, 25 January 1974, and by the Pioneer 11 Principal Investigators in *Science*, N.Y., 188, No. 4187, 2 May 1975.